Simulation of Supersonic Military Aircraft Jet Noise

K. Kailasanath, J. Liu, and R. Ramamurti
Laboratory for Computational Physics and Fluid Dynamics

Background: There is a growing need to reduce significantly the noise generated by high-performance, supersonic military aircraft. The noise generated during takeoff and landing on aircraft carriers has direct impact on shipboard health and safety issues. Also, noise complaints are increasing as communities move closer to military bases or when there are changes due to base closures and realignment. There is a significant amount of literature dealing with noise reduction in civilian, subsonic aircraft; some of the techniques found effective for those aircraft might be applicable for supersonic military jets. A distinct difference between civilian aircraft engines and advanced military aircraft engines is that military engines tend to have low bypass ratios and high velocities. During certain flight conditions — such as during takeoff or landing — the exhaust from these engines tends to be non-ideally (under/over) expanded. Non-ideally expanded exhaust flows contain shock cells in the jet exhaust, causing high-amplitude screech tones and broadband shock-associated noise, components that increase the overall noise level. Therefore, our current research is focused on understanding these non-ideally expanded exhaust flow conditions and characterizing the noise sources, so that noise reduction techniques may be successfully pursued.

Approach: A monotonically integrated large-eddy simulation (MILES)[1] approach has been developed at NRL to simulate computationally the flow dynamics and near-field acoustics of supersonic jet exhaust flows. A finite-element flow solver[2] using unstructured grids allows us to model the jet exhaust nozzle geometry accurately, and the MILES approach directly computes the large-scale turbulent flow structures. No explicit subgrid scale model is used and the modeling of the subgrid scales is implicitly provided by the embedded flux limiter in this approach.

Numerical simulations can play a significant role in the test and evaluation of various noise reduction concepts, but for the results of the simulations to be credible, they need to be compared to and evaluated against relevant experimental data. The experimental conditions should include geometries and flow conditions that are representative of realistic engine configurations and operating conditions. The simulations in this study were compared to experimental data obtained at the University of Cincinnati (UC).[3]

The jet exhaust nozzle geometries used in this research are representative of realistic engine nozzles in use on military aircraft and were designed by GE Aircraft Engines. These nozzles do not have smoothly varying contours. Instead, they are convergent-divergent nozzles: they typically have a conical converging section, a sharp throat, and a conical diverging section, a design which allows the area ratio (ratio of the area at the throat to the area at the exit of the nozzle) to be changed in flight to adapt to local conditions and thrust requirements.

Numerical Simulations of the Flow Field and Noise: Monotonically integrated large-eddy simulations of imperfectly expanded jet flows from a convergent-divergent nozzle with a design Mach number of 1.5 were carried out. Total pressure ratios ranging from over-expanded to under-expanded jet conditions were investigated. A typical computed flow field from the nozzle exhaust is shown in Fig. 4. The quantity depicted in the figure is the non-dimensional density (non-dimensionalized using the background ambient density). Key features of the flow field are also identified. Results showed that spacing of the shock cells and the length of the potential core (an indicator of jet mixing) increased as the total pressure ratio increased, and these results were in good agreement with experimental data from UC. The good agreement suggests that the computations are resolving the details observed in the laboratory experiments.

In principle, no shocks or other pressure waves are expected at the design condition. Unexpectedly, weak shock cells were observed at the design condition. Experiments confirmed this observation. Results from the simulations have identified the cause of these waves to be the sharp contraction at the nozzle throat. Hence, these studies suggest that the flow fields from realistic military engine nozzles are not likely to be shock-free under any operating condition.

Comparison of the Noise Spectra: Near-field sound pressure level (SPL) spectra at various locations in the exhaust flow were calculated and compared with the experimental measurements at UC. A screech tone was observed in both experiments and simulations, and both the intensity and frequency were in good agreement between the numerical predictions and the experimental measurements (see Fig. 5). The good agreement highlights the complementary nature of the two approaches. Since it is difficult to measure sound pressure level inside the jet experimentally without modifying the jet, measured data from inside the jet is not available. In the simulation, the fine grid (used for resolving the details of the flow) is restricted to a region close to the nozzle exit due to the limitations of current computer resources (it would be prohibitively

expensive to grid the entire flow flow field using the fine grid). Therefore, the direct overlap between the computed region and the region where detailed measurements were taken is small. However, the transition between the results from the simulations and those from the measurements is almost flawless (as seen in Fig. 5) and shows that the two approaches together can produce a more complete picture of the noise field than can be obtained by either approach alone. Further analysis of the results has provided new insight into the sources of jet noise and has been reported elsewhere.[3]

Concluding Remarks: Our simulations were able to accurately describe the flow field and noise from supersonic military aircraft jets. The excellent agreement shown between the results of our simulations and the measurements made at the University of Cincinnati indicates that such experiments and simulations can play complementary roles in the investigation of noise generation from supersonic jet flows. This was the first step in a multi-year effort. After this successful initial step to validate the computational methodology and characterize the noise sources, work on specific noise reduction techniques has begun.

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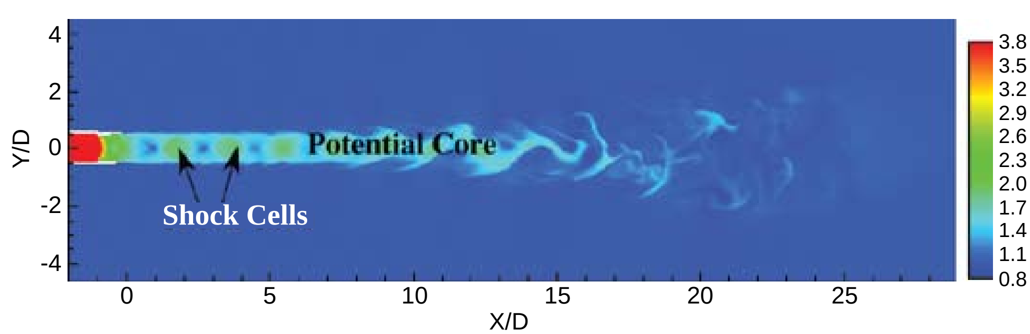

FIGURE 4
Normalized density distribution showing the key features of the computed flow field from the exhaust nozzle of a supersonic jet.

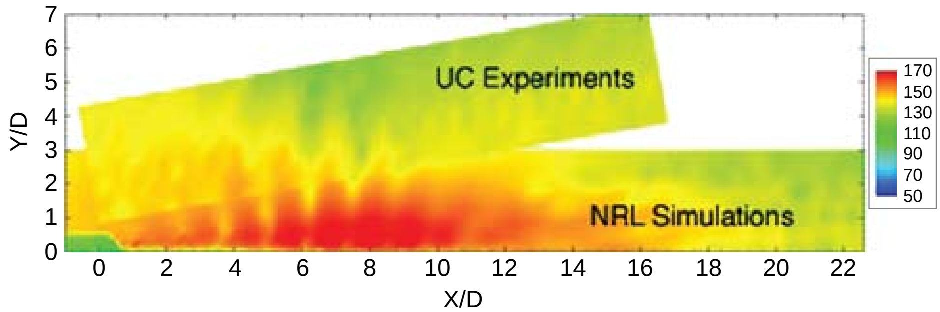

FIGURE 5
Sound pressure levels from the exhaust nozzle of a supersonic jet: comparison of simulations and experimental data. The axial (X/D) and radial (Y/D) distances are non-dimensionalized by the jet diameter (D) at the nozzle exit.